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NONDESTRUCTIVE TESTING METHODS TO PREDICT EFFECT OF DEGRADATION ON WOOD: A CRITICAL ASSESSMENT

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NONDESTRUCTIVE TESTING METHODS TO PREDICT EFFECT OF DEGRADATION ON WOOD: A CRITICAL ASSESSMENT.

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Forest Products Laboratory, Forest Service
U.S. Department of Agriculture

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ABSTRACT

Results are reported for an assessment of methods for predicting strength of wood, wood-based, or related material. Research directly applicable to nondestructive strength prediction was very limited. In wood, strength prediction research is limited to vibration decay, wave attenuation, and multiparameter "degradation models." Nonwood methods with potential application to wood include spectral response and techniques based on the ratio of energy dissipated per bending cycle and bending elastic energy at maximum amplitude.

Conclusions drawn summarize the current status of nondestructive strength prediction research in various materials. Several research options are discussed for nondestructively predicting strength loss in treated piling.

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NONDESTRUCTIVE TESTING METHODS TO PREDICT EFFECT OF DEGRADATION ON WOOD: A CRITICAL ASSESSMENT

By

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INTRODUCTION

Strength loss in wood due to chemical, physical, or biological degradation has produced concern among users of wood products. As an example, marine piling impregnated with high loadings of such salt treatments as copper arsenate have shown severe degrees of wood embrittlement. Strength losses have been manifested by the occurrence of numerous piling failures while the pilings are being unloaded from trucks, driven into place, or struck by ships while in service.

The U.S. Navy has become increasingly concerned about these treatment-related strength losses. They requested the Forest Products Laboratory (FPL) to prepare a cooperative research plan to determine the feasibility of using nondestructive testing (NDT) procedures to predict and estimate strength losses in commercially treated pilings. Prior to any experimental effort, however, FPL agreed to conduct for the Navy an assessment of nondestructive testing methods for predicting strength of wood, wood-based, or related materials.

The study conducted by FPL was based on both a literature search and a letter contact of major international research organizations. This resulted in insights on many materials other than wood.

Much of the activity in NDT research has dealt largely with nonwoody, manufactured materials such as metals, polymers, ceramics, composites, and concrete. In many materials the primary research emphasis has been qualitative, with much research effort directed toward nondestructively detecting and characterizing intrinsic material flaws. Such flaws typically occur in the manufacturing process and are often quite minute in size.

As a result of this concern for flaw characterization, limited research has been reported on nondestructive prediction of mechanical properties

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1/ Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

by NDT methods. Researchers reporting on mechanical properties prediction have worked with diverse types of materials and with varying research objectives; thus the experimental and analysis procedures vary substantially even though in each case "standard" methods were generally followed In this study it was necessary to establish procedures to screen the diverse variation in experimental and analysis procedure.

Our study emphasis was on strength prediction techniques as opposed to results of other studies on effect of degradation on material properties. The treatment process can have measurable effect on wood strength, particularly bending (25,26,38,44).[2/] These strength losses can occur as a result of either or both of the following: (1) the preservative used; (2) an unusually severe or improperly controlled treating process.

We had hoped the literature would contain numerous discussions of the effect of degradation on material strength. This has not been the case. Therefore, any data-based conclusions as to what potential a particular technique might have for predicting strength depend on results of static tests on treated wood. These results (25,26,44) show that, in the bending mode, modulus of elasticity is slightly reduced and modulus of rupture reduced somewhat more, typically between 10 to 25 percent. This lack of discussion in the literature on effect of degradation on material strength will be discussed further in the conclusion of this report.

This is a final report of the assessment. Results will be presented in several categories where each nondestructive testing method will be examined for merit as a predictive technique for estimating strength in commercially treated wood piling. Recommendations for further research activity related to prediction of strength loss in degraded material will be made in the conclusion of this report.

APPROACH

The intent of this study is to assess, through both the world literature and contact with other scientists, the suitability of current work at other laboratories. This work relates primarily to principles and techniques for strength prediction that may lead to practical nondestructive tests relevant to treated wood. Included is a discussion of existing instrumentation where the review suggests that such instrumentation is feasible for wood and wood-base materials.

2/ Underlined numbers in parentheses refer to literature cited at end of report.

Procedures for making both the literature search and letter survey and screening the references obtained are reviewed in appendix A.

Since the exact type of bending failure in the pilings is unknown, the study focuses on both static and impact bending. Therefore, the term "strength" is used to imply either static or impact bending strength, or energy absorption.

RESULTS

As discussed in the procedures (appendix A), results will be presented under one of six categories according to the nondestructive testing (NDT) methodology used. The categories are:

- Stress wave average velocity
- Resonant vibration
- Acoustic emission
- Response spectra
- Stress wave attenuation
- Miscellaneous

Reviews of abstracted references and letter responses presented in this section have been screened several times prior to inclusion in this report. Therefore, by including a description of a particular method we imply that, according to our predetermined screening procedure, the method has potential for predicting strength loss in treated wood piling.

Stress Wave Average Velocity

This category is divided into two parts depending upon the nature of the wave propagated in the material. The two wave types correspond to ultrasonic and impact-induced compressional waves.

Ultrasonic

Ultrasonic wave velocity measurement techniques, similar to that diagrammed in figure 1, have been reported in the materials literature (1,6,8, 11,19,34,35,37,42,45,50,62,65,67,72,75,77,81,84,86,88) and from contacts in the letter survey (C29, letter responses found in appendix C).

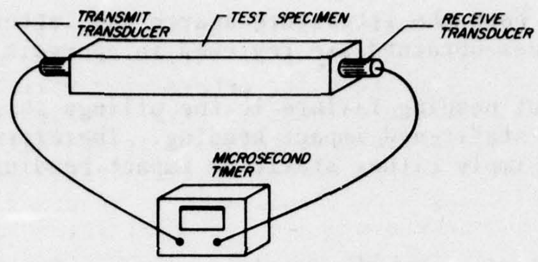

Figure 1.--Diagram of general nature of the ultrasonic wave average velocity technique.

(M 146 340)

The technique is used to measure transit time and calculate an average wave velocity (c) over a predetermined distance. An ultrasonic modulus of elasticity ($E_u = c^2\rho$) for the test specimen can be calculated using average wave velocity and average material density (ρ). Elvery and Nwokoye (17) used E_u to predict, with good results, compression modulus of elasticity (r = 0.96), static bending strength (r = 0.916), and dynamic (vibration; r = 0.873) modulus of elasticity for individual laminae, of several species of wood, used in glued laminated beams. The authors also report using specific acoustic impedance (ρc) to predict (r = 0.994) compressive strength and E_u to predict (r = 0.987) tensile strength in individual laminae used in glued-laminated beams.

Strength prediction in concrete using ultrasonic pulse velocity technique has been used extensively as reported by Clifton (14) and Malhotra (46) Clifton summarized the work of several authors in which three commercially available ultrasonic devices were used to nondestructively predict compressive and flexural strength in concrete. While the correlation of wave velocity (c) against strength properties gave good results, aggregate type and quantity in addition to mix proportions (cement-water) affect the degree of correlation. Elvery and Vale (18) describe, in detail, the operation of one of three commercially available ultrasonic pulse velocity instruments for NDT of concrete. The description includes a discussion of the characteristics of the transmitted pulse, factors influencing pulse shape and amplitude, and estimates of transit time measurement error.

Several references in this report describe pulse velocity NDT for predicting strength of various materials in situ. Drysdale (16) describes a study using pulse velocity technique for determining variability of compressive strength in concrete columns in situ. Pulse velocity was measured perpendicular (transverse) to column longitudinal axis at several positions along the length of each column tested. Actual strength was determined using a calibration curve relating strength and pulse velocity for each concrete mix design. Coefficient of variation of concrete strength within columns was used to compare differences between columns, location within column height, column size, storey location, and buildings. Agi (C2) describes an ultrasonic pulse velocity procedure used commercially by his company to test inplace marine piling. The procedure measures the remaining sound cross-sectional area of the piling; from these data, individual column analysis, and overall structural analysis are carried out. The procedure, according to Agi, has been used quite successfully for some 17 years.

Measurements of surface and near-surface average velocities in fiber-reinforced composite were made by Schultz (69) using what he called an interval velocity technique. It involves transmitting an ultrasonic pulse into a panel via the wide surface. Two receive transducers spaced 1 inch apart and positioned some distance from the transmitter measure the elapsed time for the wave to travel between receive transducers. Using measured wave velocity and local density, obtained by radiometry techniques, the author calculated a localized ultrasonic moduli. Regression of localized ultrasonic versus flexural modulus showed that a majority of data points fell within ± 15 percent of the regression line. The good correlation, the author suggests, was due to flexural modulus values for composite panel product tending to be more closely related to near-surface ply properties rather than the bulk panel properties.

Ultrasonic through-transmission technique has been reported extensively in the literature (85,87), primarily as a technique for characterizing intrinsic flaws in manufactured materials such as reinforced and laminated composites. Through-transmission techniques have been used by Zurbrick (87) for measuring variability in elastic moduli in the thickness direction of epoxy resin composite panels. Elastic moduli ($E = c^2\rho$) measured in both the panel thickness direction and panel ply plane direction were shown to be related to panel tensile modulus in the same manner, except for differences in the intercept of the linear regression line.

Several researchers have used ultrasonic average velocity techniques to measure stresses in aluminum alloy and concrete. In aluminum alloy Noronha, Chapman, and Wert (51) showed that changes in transit time of surface and shear waves can be related to the applied stresses. Results

of this work showed, for surface waves, a linear relationship between applied tensile stress and change in transit time (Δt). This property of the material, the author suggests, is attributed to the effect of higher order terms in the elastic moduli of the material.

In concrete, Urzhumtsev and Medvedev (80) found that ultrasonic velocity varied significantly for loads of from 50-80 percent of ultimate compressive strength in concrete cylinders. The authors hypothesized that the rupture surfaces in the bulk material lengthened the ultrasound path and as a result increased the wave transit times. Coefficient of absorption ($\alpha_{\parallel}$) of vibration energy at ultrasonic frequencies increased with load. It was hypothesized that increases in absorption resulted from increases in wave scattering due to heterogeneities (cracks) and growth of these heterogeneities under applied stress. A linear regression of

$\alpha_{\parallel}$ versus $\frac{\sigma}{R_{szh}}$ (applied stress over ultimate compressive stress)

gave a correlation of 0.993.

Impact-Induced

Impact-induced stress wave velocity instruments similar to that diagrammed in figure 2, differ from their ultrasonic counterparts only by the nature of the wave that is propagated in the test specimen. An impact-induced stress wave instrument described by Gerhards (22) produces a compressional wave which propagates in the test specimen at sonic speed. Transit time is measured on the instrument's microsecond timer and used, along with path length, to calculate average wave velocity. An average stress wave modulus of elasticity ($E_{sw} = c^2\rho$) can be calculated from average wave velocity (c) and average density (ρ). There is a need to impact the test specimen on a free surface such as the end and therefore, the impact device without modification is not well suited to in situ wave velocity measurements.

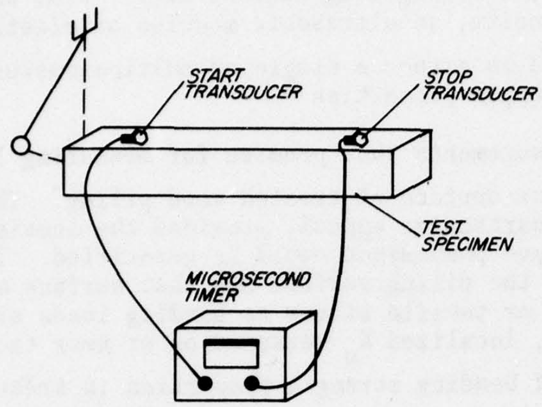

Figure 2.--Diagram of an impact-induced stress wave average velocity measuring technique.

(M 146 339)

Pellerin and Morschauser (57) describe an experiment in which the impact-induced stress wave parameter $\frac{1}{\Delta t^2}$ was used to predict particleboard modulus of elasticity (MOE) and modulus of rupture (MOR). Results show correlation coefficients (r) of 0.93 and 0.95 for predicting MOE of two different particleboard samples and correspondingly, 0.87 and 0.93 for prediction of particleboard MOR.

Remarks

Ultrasonic wave velocity techniques have been used extensively in NDT of materials as is suggested by the number of papers cited in this part of the report. This use of the stress wave average velocity technique, including the ultrasonic and impact-induced wave velocity methods, stems from the ease of application both under controlled conditions and *in situ*, relative small capital investment for measuring equipment, and excellent results in predicting several material properties using E_u or E_{sw}. Application of the technique to strength loss prediction in treated wood piling has not been reported in the literature but limited additional research could identify whether a before- and after-treatment effect can be measured using wave average velocity techniques.

The actual testing of piling would likely involve measuring average wave velocity parallel to the piling longitudinal axis. From wave velocity and piling average density, an ultrasonic modulus of elasticity (E_u) can be calculated and used in either a single or multiparameter model for predicting piling strength properties.

Interval velocity measurements show promise for measuring localized E_u in the surface and near-surface of treated wood piling. This type of measurement may have particular appeal, provided the sensitivity to surface and near-surface phenomenon could be quantified. The treating chemicals reside near the piling surface and that surface material is put under compressive or tensile stress as bending loads are applied to the piling. Therefore, localized E_u measured on or near the surface may be a good predictor of bending strength properties in treated piling.

Prediction of residual stress using Δt, with additional development, has perhaps some potential for estimating failure strength in wood members such as treated piling. The additional development might take the form of estimating failure stress at some point well below the proportional limit, given a plot of stress versus Δt for low level load.

To date through-transmission wave velocity measurements perpendicular to wood piling longitudinal axis apparently have not have been used for strength prediction. However, with additional research the through-transmission technique could potentially be applied to treated piling in a fashion similar to what Drysdale (16) describes for concrete columns, using the physical approach Agi (C2) describes for marine piling.

The key to using ultrasonic and impact-induced wave velocity technologies for predicting strength loss in treated piling is to identify what changes the treating process imposes on the results of the wave velocity technique. These imposed changes must be quantified and integrated into the prediction process or model. To date, the literature survey and letter responses indicate that no one has quantified these changes.

Vibration

Resonant vibration nondestructive testing involves mechanically vibrating a test specimen in a torsional, transverse, or longitudinal vibration mode over a range of frequencies, including the fundamental vibration mode of the test specimen. The amplitude of vibration of the specimen response is plotted against frequency to obtain a frequency response curve similar to that shown in figure 3.

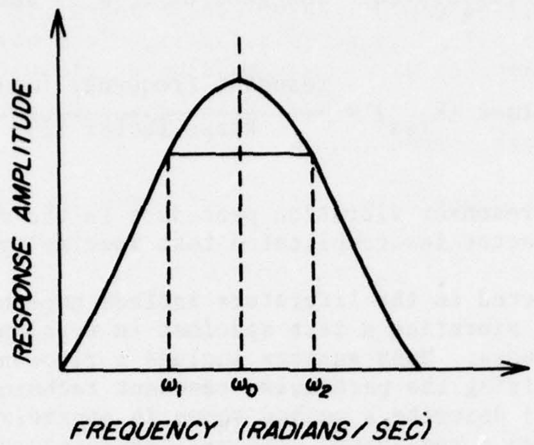

Figure 3.--Frequency response curve obtained from forced vibration.

(M 146 343)

From the resonant frequency response curve for a particular test specimen, several specimen quality factors can be calculated. These include sharpness of resonance (Q) which can be related to a damping factor (ζ) according to the equation

$$Q = \frac{\omega_o}{\omega_2 - \omega_1} = \frac{1}{2\zeta} \qquad (1)$$

where,

ω_2, ω_1 = half-power points (3 db down from amplitude at ω_o)

ω_o = fundamental mode resonant frequency

From the fundamental mode resonant frequency (ω_o) and a calculated specimen shape factor (I, moment of inertia) a resonant modulus of

elasticity (E_{res}) can be calculated. The general form is shown as:

$$\text{physical constant } (E_{res}) = \frac{\text{resonant frequency } (\omega_o)}{\text{shape factor } (I)} \qquad (2)$$

One disadvantage of the resonant vibration procedure is the difficulty in calculating a shape factor for complicated test specimen geometries.

Resonant techniques reported in the literature include numerous detailed methods for mechanically vibrating a test specimen in torsional, transverse, or longitudinal modes. Many authors include a rigorous development of the theory underlying the particular resonant technique. Brown, Hancox, and Reynolds (10) describe a method shown in appendix B, (fig. B1) for mechanically vibrating a rod-shaped carbon-fiber-reinforced plastic (CFRP) specimen in either torsional or longitudinal modes. From a resonant frequency response curve, the authors calculated either Young's modulus from longitudinal resonant frequency or shear modulus from torsional resonant frequency. These results were compared to the static values in bending and torsion. In general the results indicated that dynamic Young's modulus over-estimated static bending modulus by 5 to 30 percent depending somewhat upon the surface treatment applied to the individual carbon-fibers. Static shear moduli, using the resonant frequency response curve generated from torsional vibration, were over-estimated by approximately 10 percent.

Popescu (61) used what he called a coupled oscillation principle to generate bending and torsional oscillation in hardwood test specimens. The device used to produce these vibrations is diagrammed in appendix B, (fig. B2). Bending and torsional oscillations are produced in the test specimen by two pendulums of identical weight. The pendulums are coupled to the sample and generate a beat frequency in it due to the interference between the pendulum oscillations and natural oscillation of the test specimen. Either bending or torsional oscillations are produced in the specimen according to the mode of pendulum oscillation. Relationships between bending or shear modulus and the beat frequency generated by the pendulum were derived by the author. A plot of ultrasonically determined elastic modulus versus coupled oscillation measured E, shown in appendix B, (fig. B3) shows good agreement of the variables along the diagonal.

Papadakis (55) describes a balanced resonator for measuring modulus of elasticity and logarithmic decrement for specimens in flexural vibration. The balanced resonator operates in flexure at "far infrasonic" frequencies which, the author claims, give a modulus of elasticity more consistant with static flexural values than with elastic modulus values determined

ultrasonically. Papadakis suggests that this agreement with static flexural modulus of elasticity results from measurements taken at (1) low levels of strain falling below all the relaxation [Mears (49)] of significance in the material and (2) very low equivalent strain rates. Schematically, the balanced resonator is shown in appendix B (fig. B4).

The test specimen oscillates in flexure in a plane perpendicular to the page in appendix B (fig B4, right). Specimens are driven in oscillation electrically to obtain the resonant frequency response curve shown previously in figure 1. Balanced resonator techniques were used to measure Young's modulus and logarithmic decrement (δ), in lucite bars, as a function of temperature. In forced vibration, logarithmic decrement is defined as

$$\delta = \pi \frac{(\omega_2 - \omega_1)}{\omega_o} \tag{3}$$

where resonant frequency ω_o is the peak frequency on the response curve while ω_2 and ω_1 are frequencies at the half-power points. Changes in Young's modulus and decrement as a result of physical and chemical changes, due to temperature, in the lucite bar could not be explained by Papadakis. The analysis of the data consisted of presenting several graphs showing variations in Young's modulus as a function of temperature.

Kovacs and Cole (40) demonstrated that the dynamic elastic modulus (DEM) of iron castings vibrated longitudinally was a considerably more accurate strength predictor than ultrasonic velocity. The authors used the instrument schematically shown in appendix B (fig. B5) to generate longitudinal vibrations in the test specimen. A resonant frequency response curve similar to that shown in figure 1 was obtained for an individual iron casting test specimen. From the calculated dynamic elastic modulus, the authors predicted yield and tensile strength with good accuracy. Results showed that for a DEM of 24.2×10^6 lb/in.^{2}, the yield strength in iron castings of 63,000 lb/in.^{2} was predicted to within $\pm$ 2,300 lb/in^2. At the same DEM, tensile strengths of 85,000 lb/in.^{2} were predicted within 7,500 lb/in.^{2}.

Several authors (7,33) reported using a transverse vibration method described by Kline (39) for obtaining a resonant frequency response curve. A bending elastic modulus was calculated from the fundamental mode resonant frequency obtained off the response curve. A diagram, schematically showing the method of suspending the test specimen is shown in figure 4.

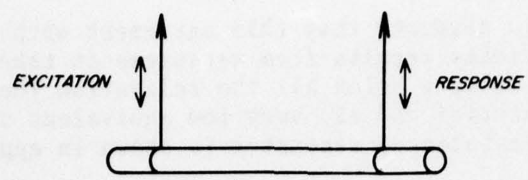

Figure 4.--Diagram showing the method of suspending a transverse vibration test specimen.

(M 146 342)

The specimen is suspended by cotton threads at the approximate calculated position of the nodes for fundamental mode transverse vibration. The suspended specimen is excited through one thread and the accompanying specimen response is measured through the other thread. Jenness and Kline (33) compared, for several epoxy-matrix composites, the modulus of elasticity obtained by this dynamic method and a static flexural method. The ratio of the dynamic modulus to static modulus varied from 0.94 to 0.98, indicating that the dynamic modulus agreed quite closely with the static flexural modulus of elasticity. Plots of flexural strength versus dynamic modulus gave points in a fairly narrow band over a range of dynamic moduli. Lower flexural strengths indicated by the lower dynamic modulus values coincided with failure in the material due to matrix voids. Jenness and Kline (33) indicated that these deviations in dynamic modulus from nominal values may serve as a nondestructive test for predicting void content in addition to strength.

Blankenhorn, Kline, and Beall (7) used the flexural resonance method described by Kline (39) to determine dynamic mechanical properties of black cherry wood as a function of temperature at audio frequencies. The authors presented graphic results which show that dynamic elastic modulus and internal friction of black cherry varied substantially as a function of temperature (100° to 600° K) and moisture content (up to 20 pct).

Jensen (34) described a sonic means of detecting internal decay in wood poles. Excitation was provided through either a single impact or a forced vibration. Test results showed that sound, treated Douglas-fir poles had a single mode of vibration near 2,500 Hz. Poles with internal decay had amplitudes and frequencies of vibration which varied as a function of extent and location of internal decay. A patent was

awarded to Harris (27) for an ultrasonic pole testing device for detecting decay in wood poles.

A free transverse vibration procedure is described by Pellerin (56). The procedure varies from the previously described procedures in that, rather than continually being driven, the specimen is displaced initially and allowed to vibrate at a fundamental frequency consistent with the support conditions. Vibrations decay with time as shown in figure 5.

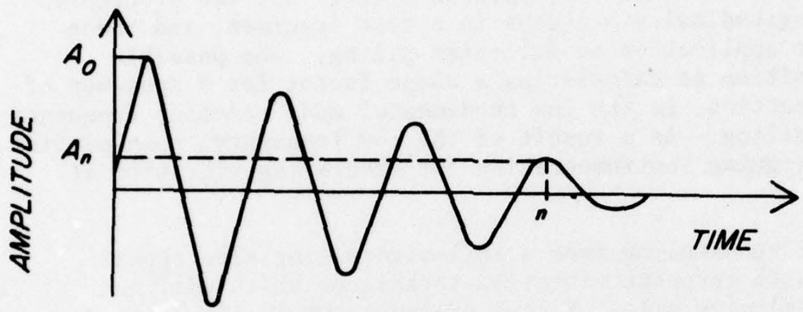

Figure 5.--Free transverse vibration decay envelope.

(M 146 345)

Pellerin calculated a logarithmic decrement (δ) and, together with a dynamic vibration modulus (E_d), predicted modulus of rupture in construction lumber (6 pct moisture content) with correlation coefficients varying from 0.90 to 0.92.

Several authors including Hearmon (30), Bertholf (5) and Brenndörfer (9) have extensively reviewed the vibration theory as it applies to wood.

Remarks

Resonant vibration procedures, as reported in the literature for nondestructively measuring dynamic elastic modulus and internal friction, involve relatively small specimens of simple geometry. A simple specimen geometry minimizes the difficulty in calculating a shape factor in the equation relating fundamental resonant frequency to the dynamic modulus of elasticity. In this regard, the taper in full-size treated piling may present difficulty in calculating an appropriate shape factor if the entire piling is to be vibrated. Because of piling size, many resonant

vibration techniques reported in this part of the review would appear to be difficult or nearly impossible to apply.

By making simplified assumptions about the extent of taper in full-size piling, many resonant vibration procedures described in this review and capable of handling large specimens may have possible application. The balanced resonator used by Papadakis (55) has potential application; however the two large end masses would have to be made of sufficient size to produce flexural vibrations in the piling. Kovacs and Cole (40) described instrumentation shown in appendix B (fig. B5) and procedures for generating longitudinal vibrations in a test specimen, and these have potential for application to full-size piling. One possible difficulty, in addition to calculating a shape factor for a specimen of nonuniform cross section, is the low fundamental mode resonant frequency of the full-size piling. As a result of the low frequency, some problem may develop in designing instrumentation for generating vibration at this frequency.

The possibility of subsampling from a full-size piling also appears feasible for use with resonant vibration techniques which will not accommodate the full-size pile. Such a procedure would also provide flexibility in working with less complex specimen geometries. Data collected on the subsample could be incorporated into a model to predict full-size pile properties.

Free transverse vibration techniques as described by Pellerin (56) for calculating logarithmic decrement (δ) and a dynamic vibration modulus of elasticity (E_d) could be used for full-size piling. This again would depend on the difficulty in calculating a shape factor and vibrating a specimen of the cross-sectional size of a piling.

Resonant vibration techniques reported in the literature involve a wide variety of procedures for vibrating a test specimen, few of which appear to be easily adaptable to piling size specimens. Free transverse vibration, however, does appear to have potential for application to piling size specimens. In such an application, transverse vibration techniques would be used to identify the effect of treatment on specimen response, which would in turn be related to the amount of strength loss due to treatment.

Acoustic Emission

Acoustic emission techniques described in the literature have been used extensively for characterizing flaws and monitoring crack growth in nonwoody materials such as metals, polymers, and concrete. Several

authors described acoustic emission techniques for assessing structural integrity and strength of structural size components. In this application the test specimen is loaded in one of several modes, such as bending or tension. Acoustic emissions from the specimen under test are monitored by a piezoelectric transducer. Data recorded from the test typically includes plots of emission count versus load and strain versus load.

Arrington and Evans (2) described the results of a preliminary feasibility study on the application of acoustic emission testing for assessing structural integrity of high alumina cement concrete. Mechanical tests on beams in this study included both static uniform loading in bending, and selective loading in either shear or tension. The study also included data from compression tests on concrete cubes. After analyzing the plotted data, the authors concluded that various interpretations of the plots yielded good assessments of structural integrity in the test beams. These interpretations of structural integrity were made from:

(1) Increase in slope of emission-load curve was precursor to failure, at approximately 90 percent of the failure load.

(2) Higher number of emissions recorded during loading hold period, usually indicated impending failure.

Pollock (60) used acoustic emission techniques to detect poor adhesion in metal-to-metal bonds. Plots of emission-load showed that poor adhesion was indicated by numerous emissions at low stress levels.

Porter, El-Osta, and Kusec (64) used the acoustic emission setup shown in appendix B, (fig. B6) to estimate ultimate bending strength in nominal 2 x 6 inch Douglas-fir finger joints. The specimens were loaded flatwise and in a configuration such that the finger joint fell in the middle of the 48-inch span. Load versus cumulative acoustic emission was plotted for several finger joint types. For predicting failure in the finger joints, the authors hypothesized that, when the slope of the load-count curve goes to zero, failure would occur. Based on this hypothesis the absolute percentage error in predicting failure varied from 1.8 to 25.0 percent of failure load. This percentage varied as a function of the load at which prediction was made and nature of the finger joint. The authors indicated that, for normal commercial finger joint stock, obtaining load and emission data for a load level just beyond the proportional limit should permit estimates of failure load accurate to within ± 10 percent.

Remarks

Acoustic emission research for nondestructively predicting material strength has not been reported extensively in the literature as is

evident by the brief summary presented above. The technique may have potential for predicting failure strength in full-size treated piling based on the general character of the emission count-load curve plotted at load levels below the proportional limit. It would, however require much additional research to identify whether such an application has potential. Acoustic emissions could be explored further for potential in screening strength-reducing treatment effects in treated piling in a fashion similar to that used by Pollock (60) to identify poor adhesive bonds. This procedure would involve plotting curves of emission versus piling load and ascertaining whether numerous emissions at low load levels was a reliable indication of reduced piling strength.

Acoustic emission techniques have potential for *in situ* strength prediction application where individual piling can be loaded independently and the accompanying emissions monitored.

Response Spectra

Response spectra techniques (29,43,47,66,C25) involve mechanically exciting longitudinal and transverse resonant frequency modes in a test specimen. The resonant responses of the test specimen are recorded and analyzed using a fourier transform to obtain the component frequencies making up the specimen response. The resulting component frequencies of the response are tabulated and plotted on a graph of amplitude versus frequency.

Mattei and Shapton (47) excited the longitudinal resonant frequency in rod-shaped metal bars of Nitinol suspended horizontally by two small threads. Each rod was impacted with a hardened steel ball 1/4 inch in diameter. Rod response frequencies were detected by microphone and fourier component frequencies obtained. Equations for the frequency of longitudinal vibration of a continuous beam were used to establish the mode order of each component frequency. Young's modulus (E) was calculated for the first and second order mode of longitudinal vibration. Results of the experiment indicate that by using spectral response techniques the author could predict Young's modulus within $\pm$ 100,000 lb/in.^{2} in 13 million lb/in.^{2} using the first or second order mode frequencies.

Lloyd, Joinson, and Curtis (43) describe a spectral response technique using a steel rod (5 mm diameter by 30 mm long) to impact a metal bar containing artificial defects of either a hole or a saw cut on a line perpendicular to the longitudinal axis of the bar. Results were largely qualitative and indicated that saw cuts identical in width to the test bar produced the most significant modification in the frequency modes of the bar. Bars with holes drilled in them show spectral changes dependent on hole size and orientation. As part of the same study the authors

described results of spectral response measurements on adhesively bonded lap joints. Results indicated that the frequency modes varied more as a function of glueline thickness than void content in the adhesive film. The authors noted considerable change in the energy distribution of the response spectra but were unable to explain or correlate these changes to variations in glueline thickness or void content.

Hastings, Olster, and Lopilato (29) transmitted ultrasonic pulses through tension test specimens cut from boron-epoxy panels in an attempt to detect degradation by observing the received spectra. Received spectra were observed before tensile loading of the specimens and after each succeeding strain increment up to specimen failure. Significant differences between spectra were noted but no systematic spectral variation caused by degradation could be recognized. Efforts to minimize experimental variation proved unsuccessful in identifying variables that produced a unique relationship between transmission spectra and degradation.

Reneker et al. (66) used vibrational spectroscopy on the polymethylmethacrylate (lucite) bar (fig. 6) to determine the effect of specific defects on the response spectra of the bar. The vibrational modes of the bar were excited by either a ball dropped onto the wide face of the bar or a glass bob pendulum impact of the end. Response of the bar was measured with a piezoelectric polymer transducer bonded to the center of the bar. The response was recorded and analyzed into its component spectrum using a fast fourier transform algorithm. An example of the resulting spectrum is shown in figure 7. Peaks in the power spectrum labeled ν_n are due to the undamped bending modes of the bar. From the mode frequencies ν_n an equation for effective bending modulus of elasticity of the bar can be calculated. A second set of peaks, labeled μ_n, are due to longitudinal modes of the bar.

An equation relating longitudinal mode frequencies, μ_n, and effective longitudinal modulus of elasticity was developed by Reneker et al. (66). To assess the sensitivity of the vibrational spectroscopy technique they carried out a series of experiments to determine the effect of mass defects, simulated cracks, and temperature-induced changes on modulus of elasticity. Qualitative results indicated that the character of the spectra were sensitive to changes in bar modulus and density. They also noted, as did Lloyd, Joinson, and Curtis (43), that cracks caused significant shifts in component frequencies, changes in amplitude of modes, or introduction of new modes depending upon the relative position of the defect. They concluded that their results indicated higher order modes could be useful for detecting defects distributed in the test specimen.

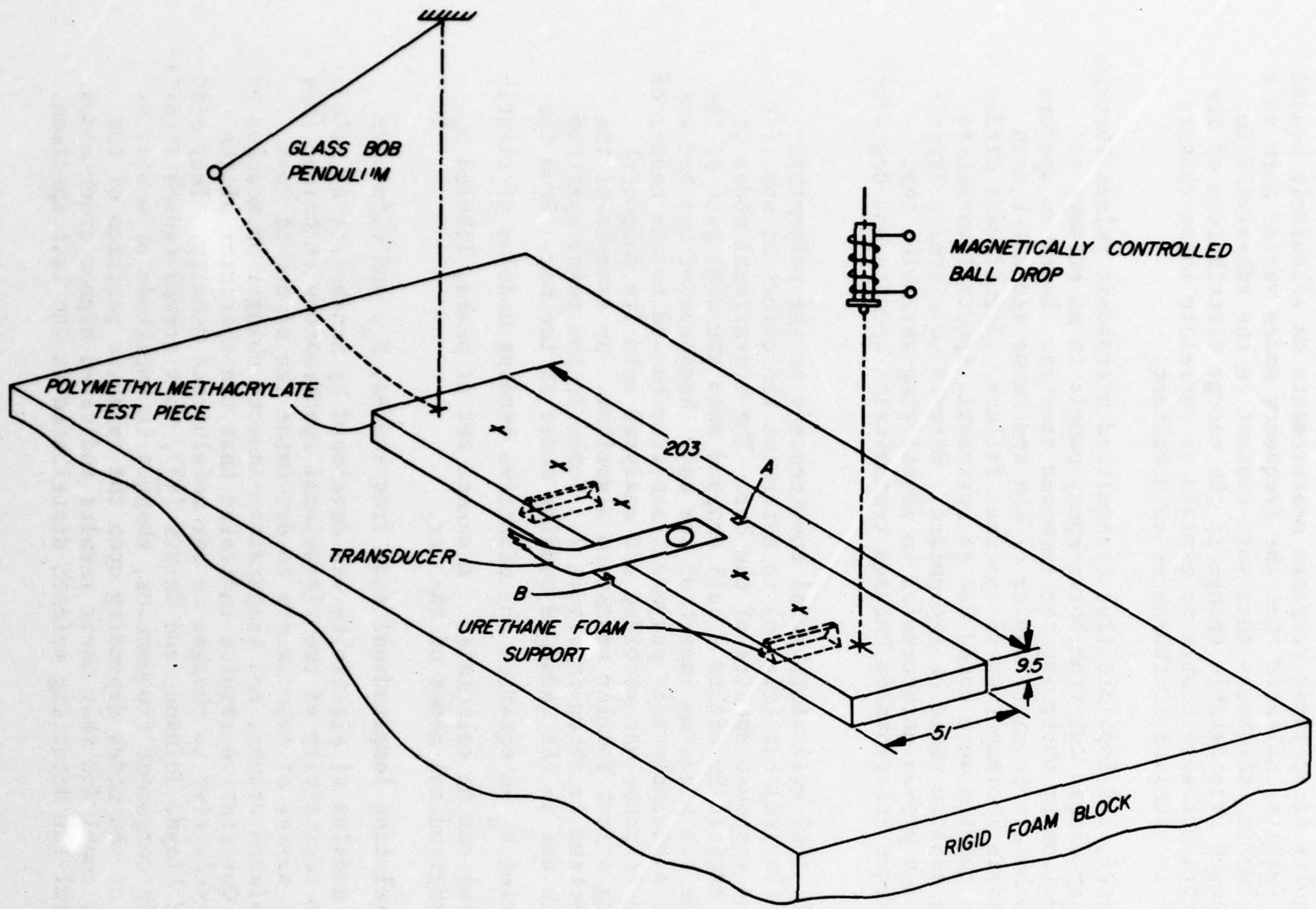

Figure 6.--Diagram of the vibrational spectroscopy set up used by Reneker et al. (66).

(M 146 483)

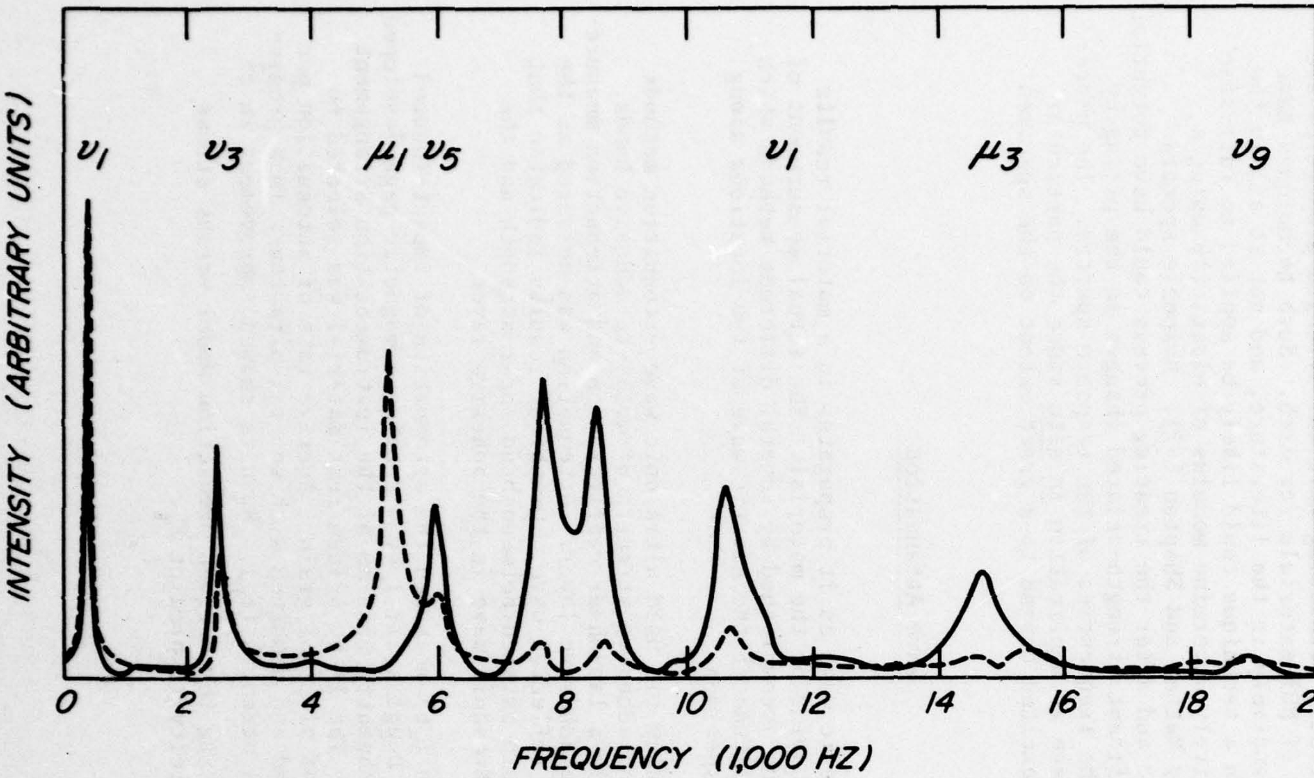

Figure 7.--Response spectrum obtained by Reneker et. al (66) as a result of impact of lucite bar diagrammed in figure 6.

(M 146 481)

Remarks

Response spectra techniques for nondestructively determining modulus of elasticity and subsequently predicting material strength properties are a relatively new area of NDT materials research. Such techniques have not been reported extensively in the literature, and not at all in the wood literature. Such a technique could likely be applied to full-size piling to nondestructively determine modulus of elasticity using a procedure described by Mattei and Shapton (47). Response spectra techniques used before and after the treating process could have potential for identifying significant strength-related changes in the piling by observing shifts in the frequencies of the response spectra. The procedure would unlikely have an application *in situ* since the particular free vibration modes excited depend to a great extent on the specimen support conditions.

Wave Attenuation

Attenuation of an elastic wave as it propagates in a material results from the inelastic behavior of the material. The actual measurement of this attenuation can be accomplished by several different methods which involve measuring amplitude of the elastic wave at two locations along the length of a test specimen.

Alers, Flynn, and Buckley (1) used ultrasonic wave attenuation methods to predict cohesive and adhesive strength of metal-to-adhesive bonds. The metal was bonded in a lap-shear configuration and attenuation measurements were made on the adhesive layer. Attenuation was measured as the ratio of incident and reflected wave. Graphical results indicated that a nonlinear relationship existed between bond shear strength and the attenuation of the ultrasonic wave in the adhesive layer.

Kaiserlik and Pellerin (36) measured the attenuation of impact-induced compressional wave in Douglas-fir 1 by 4's using a magnetic gage developed in the research. A schematic diagram of the instrumentation arrangement is shown in figure 8. The 1- by 4-inch test material was selected to have various degrees of slope of grain. Average rate of attenuation per foot (α) was calculated and combined with several parameters in a prediction model for tensile strength (F_t). Results showed improvement in r^2 from 0.697 to 0.819 using the derived prediction model versus stress wave modulus of elasticity to predict F_t.

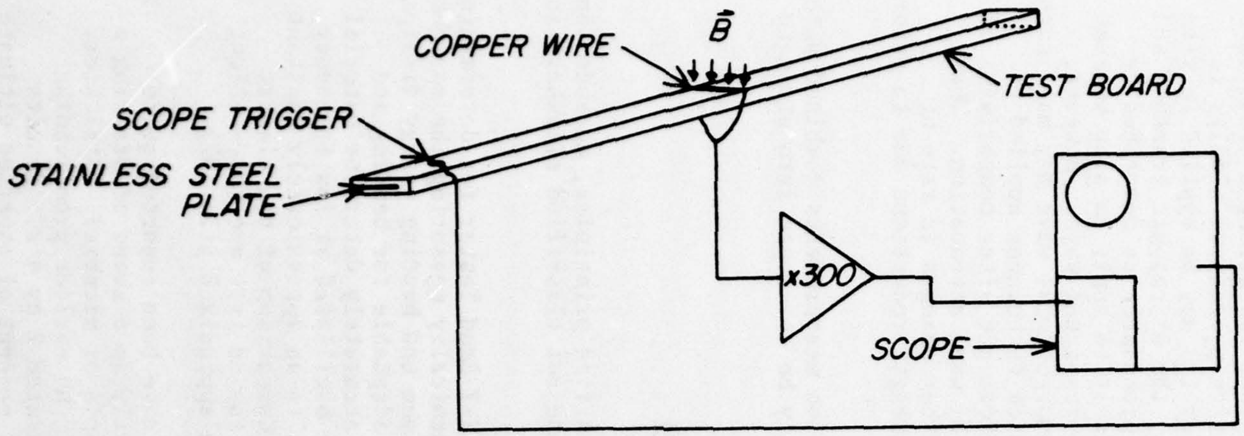

Figure 8.--Schematic of instrumentation arrangement for measuring attenuation of impact-induced compressional waves in solid lumber (Kaiserlik and Pellerin (36)).

(M 146 484)

Remarks

Although limited reference has been made in the literature to wave attenuation techniques for strength prediction, results of work reviewed above indicate some potential of this technique for strength prediction in degraded wood. Ultrasonic wave attenuation procedures similar to those described by Alers, Flynn, and Buckley (1) may be applied *in situ* where two free surfaces can be contacted by the ultrasonic transmit and receive transducers. Compressional wave procedures as described by Kaiserlik and Pellerin (36) would be difficult to apply *in situ* because of the need to mechanically induce the compressional wave. However, other means such as a thermally induced compressional wave may make such a procedure usable *in situ*. Wave attenuation techniques applied to piling appear likely to apply in making before and after comparisons of load or treatment history effects on rate of wave attenuation. These results could be analyzed to determine whether changes in rate of attenuation in the piling coincide with strength reductions due to prior loading or treatment.

With additional development, wave attenuation measurements combined with other nondestructive parameters could likely be developed into strength prediction models for piling.

Miscellaneous

This section will review previously unclassified principles, methods, or instrumentation reviewed for this survey and not classified elsewhere in the report.

Weissman (82) used what he described as a W-T Bend Tester for determining design properties of several alloys by dynamically measuring the maximum bending elastic energy stored in the specimen and bending energy dissipated per cycle. The procedure is particularly adaptable for bending and torsional tests. It allowed Weissmann to accurately determine material modulus of elasticity. Test specimens are oscillated at low frequency which, it is assumed, subject the specimen to an approximately constant bending moment for small angle rotation. Comparison of the elastic moduli measured by the bend tester and a tension test are in excellent agreement as shown by the graph present in appendix B (fig. B7).

Proofloading procedures (C11,58,59,73,74) have been reported quite extensively in the wood literature, primarily as a means of assuring a minimum strength level in a particular sample of material. Strickler, Pellerin, and Talbott (74) describe one of the earlier proofloading experiments in using Douglas-fir finger-jointed 2 by 4's. Results indicated that bending proofloads up to 90 percent of expected ultimate

bending strength did not significantly reduce the strength of the end-jointed Douglas-fir 2 by 4's. Results also showed that proofloads less than 70 percent of expected ultimate bending strength minimized the proportion of broken material. Results in hemlock indicated that a bending fiber stress approximately four times the allowable working stress in tension is necessary to account for conversion from bending to a tension proofload and adjustment to an allowable property. As a result, a bending proofload for tension members is only feasible if the factor of 4 can be tolerated. In this regard a tension proofload offers the possibility of assuring higher tensile grades for lumber than does a bending proofloading. This becomes particularly significant where the proofloaded member is under tension as in laminated beams.

Pellerin and Strickler (58,59) also demonstrated the usefulness of tension proofloading in assuring laminated beam strength for beam designs of 2,600f or higher. Research showed that tension proofloads of 2.0 times f in highly stressed tension laminations of the beam produced laminated beams with working stresses of 3,300f. Reducing the proofload to 1.4 times f yielded beam working stresses of 2,600f. The authors concluded that tension proofloading provides a means of assuring a safe, minimum design stress level for small laminated beams. Pellerin and Strickler also demonstrated (59) that proofloading would permit fabrication of large glued-laminated beams with predetermined working stresses. The test beams were constructed using proofloaded tension laminations for the outer two laminations. The remaining laminations in the beams (24 inches deep by 5-1/4 inches by 40 feet) were constructed of E-balanced L3 visual grade material. Proofload levels of 1.2 and 1.4 times allowable bending stress (f_b) were used for the two outside tension laminations. Results indicated that tension laminations number 3 and 4 appear to significantly affect beam strength, and thus, beam properties could be improved by also proofloading these laminations.

Static procedures for measuring both long- and short-span E (52,C9) have been a standard research procedure, in wood, for nondestructively measuring E and in turn using it to predict other engineering properties. Orosz (52) briefly describes these long- and short-span static E measuring procedures. Hoyle (32) and Hilbrand and Miller (31) have summarized much of the early strength prediction research which typically involved a simple model, containing E, for predicting bending strength.

Modeling procedures (C5,23) have been used by a number of researchers, particularly in wood research, to nondestructively predict lumber mechanical properties using various combinations of measureable parameters. Such parameters might include density (ρ), strength ratio (SR), slope of grain (SOG), moisture content (MC), etc. Gerhards and Ethington (23) evaluated several models for predicting tensile strength of 2- by 4-inch lumber. Their prediction models included combinations of parameters

such as strength ratio, modulus of elasticity, specific gravity, and slope of grain. Each model was evaluated and compared with others in terms of efficiency. This efficiency measure is described as the amount of useful strength in an entire lumber sample that is made available by using any particular model. Results indicated some improvements in efficiency using models of several combined parameters as opposed to the ASTM D 245 bending strength ratio model.

Orosz (53) used long- and short-span static E measurements in a multi-parameter model, including strength ratio, to predict tensile strength in 2 by 4 and 2 by 8 southern pine dimension lumber.

Bryant (C5) described a model for predicting bending, tensile, or compressive strength. The model form includes:

$$\text{Strength} = \frac{(A) \times (\text{density})}{KR^{B} + C}$$

where

A, B, and C are constants which differ for bending, tensile, and compressive strength.
KR is the ratio of the sum of the widths of all knots in a 6-inch length to the perimeter.

Preliminary results showed B to vary between 0.96 and 1.04, so a value of 1.0 was assumed without any great loss of efficiency. This reduced form of the equation follows:

$$\text{Strength} = \frac{(A) \times (\text{density})}{KR + C}$$

Bryant found that general slope of grain appeared to have a significant effect only on virtually clear timber.

Casselbrandt (C6) described in detail some of the work being done at the Swedish Forest Products Laboratory on estimating strength loss in utility poles decayed by softrot. Of particular interest was the work involving an instrument called a "Pilodyn". The instrument is fashioned somewhat after the principle of a Schmidt concrete hammer. Principle of operation is based on measuring depth of penetration of a pointed pin shot into the wood. Measured penetration is used for estimating degree of soft rot, which in turn can be correlated to strength reductions caused by

soft rot. Graphical results of early research using the Pilodyn showed a well-defined trend to data plotted for ultimate tensile stress (STR) versus soft-rot degree (SRD).

Remarks

Static bending, proofloading, and strength prediction modeling procedures described in this section appear to have application in nondestructively predicting treatment-related strength loss in full-size piling.

Static bending procedures for measuring modulus of elasticity (E) likely apply in predicting strength loss due to treatment in full-size piling. Again, some assumption may be necessary in calculating E as a result of the piling taper. The real issue, however, is whether statically determined E is sufficiently sensitive to changes in strength properties due to treatment processes.

Proofloading as a means of assuring that a group of piling has a minimum bending strength has some appeal but would require additional research. Questions to be answered by such research might include (1) Is proofloading a feasible approach for large wood members such as piling? and (2) Would proofloading of large, treated wood members produce the same positive results reported for small, untreated dimension lumber?

The principle of strength prediction using multiparameter prediction models of various forms would likely apply to strength prediction in full-size piling. The most formidable task in this research area would involve determining which combination of parameters best predicts the bending strength of treated piling and whether the model is sufficiently accurate. Parameters which might be considered for such a model include density, strength ratio, growth rate, and slope of grain.

A more complex model for strength prediction in full-size piling might include some previously described, nondestructively measured parameters such as log decrement (δ), static long- or short-span E, ultrasonic E, and resonant vibration E.

The Bend Tester (82) offers the potential of nondestructively determining small specimen parameters such as strength and E. Application to full-size piling would likely require subsampling which may be a formidable task given the nonuniformity in treatment that can exist in treated marine piling. What prediction accuracy such a device might have in going from small, subsampled specimens to large treated piling could only be identified with considerable additional research.

The Pilodyn instrument would likely have potential for predicting strength in treated piling using a procedure similar to that described

by Casselbrandt for estimating strength reduction due to soft-rot decay. Additional research would be necessary to identify whether such potential exists for using the Pilodyn in this application.

CONCLUSIONS

It is concluded from the review that nondestructive testing techniques for predicting strength in degraded materials such as treated piling have not been reported in the literature. The lack of coverage of this topic may be due largely to the fact that researchers working in various materials NDT areas often have vastly different research objectives. For instance, NDT research on manufactured materials such as metals, polymers, and composites often has the objective of determining whether the material contains certain types of defects at particular points in the manufacturing process. These defect types may range from grain-boundary defects in metals to voids in composites. One exception is concrete, in which much of the NDT research has dealth with predicting compressive strength as a function of time during the initial stages of curing. These results often vary depending on the mix proportions (cement-water) of the concrete.

A possibly more relevant exception is the reported research on strength prediction in degraded nonwoody material described by Noronha, Chapman, and Wert (51), in which they nondestructively predicted the effect of prior load history on material strength. However, the authors did not derive a degradation model for predicting strength loss as a function of load level.

Research results on nondestructive strength prediction in degraded woody material appear limited to the report discussed by Casselbrant (C6). In this report, the author showed graphical data of ultimate tensile stress (STR) versus soft-rot degree (SRD) with a second order polynomial curve fit to the data.

Many nondestructive techniques described in the literature for measuring specific material parameters are designed for small-size test specimens. This is particularily the situation with the resonant vibration techniques. Subsampling from the full-size piling would be required to apply many of these nondestructive techniques.

With exception of the stress wave average velocity techniques used by Drysdale (16) on concrete columns and by Agi (C2) on marine piling, few techniques described in the literature have been applied to anything near the size of piling and containing the natural heterogeneities of piling.

Many NDT techniques reported in the literature were developed as laboratory-type techniques. As a result, few appear to be ready to apply immediately without further research. Such research, where the technique is judged to have potential, would include adaptation of the technique to larger specimens and determining whether the parameter measured by the technique has potential for predicting strength loss in degraded material.

Our specific conclusions are summarized as follows:

1. Nondestructive testing (NDT) techniques for strength prediction in degraded materials such as treating piling have not been extensively reported in the literature.

Exceptions:

a. NDT research in concrete has utilized ultrasonic pulse velocity technique for predicting compressive strength during the initial stages of curing.
b. Noronha, Chapman, Wert (51) nondestructively predicted the effect of prior load history on material strength also using ultrasonic pulse velocity techniques.
c. Nondestructive strength predictions in degraded woody material appear limited to the work reviewed by Casselbrant (C6). The research dealt with predicting ultimate tensile stress as a function of the degree of soft rot which was measured using a commercially available penetration device.

2. Many NDT techniques described in the literature are designed for application to small-size test specimens.

3. Few of the techniques reported in the literature have been applied to specimens the size of piling and containing the natural heterogeneities of piling.

Exception:

a. Stress wave average velocity techniques used by Drysdale (16) on concrete columns and by Agi (C2) on marine piling.

4. NDT techniques reported in the literature were largely developed as laboratory-type techniques; none appear to be applicable immediately without further research.

PROPOSED RESEARCH

Discussions as to what specifically causes the wood embrittlement[3/,4/] that leads to the characteristic brittle failures in treated wood piling have pointed out that embrittlement likely results from an acid hydrolysis of the cellulose chain. The hydrolysis manifests itself in the breaking of the cellulose chains at intermediate points. The degree of hydrolysis depends largely on acidity, temperature, and time. In the piling treatment process, acidic preservatives such as copper chromated arsenate (CCA) subject to elevated temperatures cause the hydrolysis reaction to proceed at a rate dependent on temperature.

Results of previous research (25,26,38,44) have shown that the treatment process in wood has a more significant effect on bending strength than on stiffness. These differences in effect may amount to reductions in bending strength of twice that of stiffness. Therefore, any proposed nondestructive testing research must acknowledge that stiffness alone will not be an efficient parameter for strength loss caused by degrading treatments.

Any proposed nondestructive testing research should explore those techniques and methodologies which show specific sensitivity to strength reduction occurring as a result of the change in the integrity of the cellulose chains due to acid hydrolysis. Nondestructive techniques which measure elastic wave energy decay in a test specimen may fall into this category and their potential for application to this problem should be explored. Specifically, these include the transverse vibration decay technique described by Pellerin (56). In addition, impact-induced compression wave attenuation techniques described by Kaiserlik and Pellerin (36) also fall into the category of energy decay NDT techniques. Energy decay at ultrasonic frequencies should also be explored as an alternative for estimating strength loss in treated piling.

Since modulus of elasticity has been used quite successfully as a predictor for strength, in virgin material its potential as one of the parameters in a multiparameter "degradation model" must be considered. The model suggested includes, among others, nondestructively measured E and an elastic wave energy decay term.

Any of several techniques described in the section on stress wave average velocity methods would be suitable for obtaining the nondestructively measured modulus of elasticity (E) parameter for a model.

3/ Baker, A. J. 1978. Personal communication.

4/ Johnson, B. R. 1978. Personal communication.

Ultrasonic and impact-induced average wave velocity techniques are perhaps easiest to apply if test specimen density can be easily measured or adequately estimated. An end-use application would likely select one technique over another depending on test specimen size and configuration and whether measurements were made _in situ_ or by subsampling.

As a result of the potential for wood embrittlement due to treatment and the fact that treatment resides near the surface, some nondestructive surface measurements merit investigation. Such surface measurement techniques with potential for nondestructively predicting strength reductions due to embrittlement are: (1) standard ASTM D 143-52 hardness test which measures force required to penetrate a measured amount, and (2) penetration tests using the Swedish "Pilodyn" instrument described under the miscellaneous section of the survey. Each technique has potential and should be further investigated. Parameters measured by either of the above techniques might also be included in a multiparameter prediction model for estimating strength loss due to treatment.

Research

Options

Since the results of the survey have (1) provided no guidance as to what form a "degradation model" might take for prediction of strength loss in degraded virgin material and (2) identified no direct application of NDT techniques for predictng strength loss in treated full-size wood piling, we are outlining several options for further research. Each option will be briefly outlined and will include remarks as to the advantages and disadvantages of the particular option.

Option I

Explore the development of a "degradation model" based on controlled treatment experiments. The actual model developed in this effort would predict strength loss due to the treatment degradation which occurred from the untreated condition. Model parameters used either together or separately would include E, elastic wave energy decay, and hardness in addition to others. Variables in such a controlled small specimen experiment would include treatment level, size, and species.

An advantage of such an approach is that it allows for a systematic evaluation of several variables affecting treatment related strength losses. It also allows for the careful evaluation of several potential NDT parameters, for inclusion in a strength prediction model. Perhaps the overriding advantage of this approach is that it provides the guidance

to subsequent selection of strength prediction methodology. A disadvantage is the recognition that the results must be translated to full-size piling prior to effective implementation as a "degradation model."

Option II

Examine an approach in which small specimens are subsampled, according to a predetermined design, from full-size treated pilings. The subsampling design will be developed on the assumption that the piling will be loaded in bending under predetermined boundary conditions and that the preservative treatment resides on or near the piling surface. NDT techniques described earlier in this section of the report will be used to measure nondestructive parameters on the subsampled specimens. Parameters will also be measured by NDT techniques described previously as being compatible for small specimens. Measured parameters will be included in a simple model to predict specimen strength. Each model will be carefully examined to determined which parameter model most accurately predicts small subsampled specimen bending strength.

Finally, small specimen results will be applied to full-size piling to determine what strength prediction accuracy can be obtained based on these results. Actual translation of results will be either by mathematical modeling or actual testing on full-size treated piling.

An advantage of option II over option I is the potential for reduced effort in terms of scientist man-hours involved, due to a less complex experimental procedure. However, the time and effort involved in testing full-size piling, if that experimental procedure is selected, can be quite substantial as compared to small specimen tests. Disadvantages include the limited guidance and accuracy that may result in the final prediction model because treatment-related variables affecting that model were not completely identified.

Option III

This third option would explore applying nondestructive strength prediction techniques directly to full-size treated piling. The several NDT techniques identified previously in this section as potentially applicable to large piling will be used to measure nondestructive parameters on individual piling. Simple bending strength prediction models will be carefully examined to determine which model most accurately predicts full-size piling strength.

The advantage to such an approach is the relatively simple experimental design. However, the full-size pile tests may require a substantial amount of time given the test specimen size. As in option II, this

simplicity may be deceptive; the disadvantage of the less rigorous approach is the potential for limited accuracy or perhaps total lack of success of the final strength prediction model because of insufficient basic study.

Option IV

Finally, option IV would involve cutting a full-size piling in half. Half of the piling would be included in the actual treating batch and the other half would serve as an untreated control. A nondestructive strength prediction model would be developed for both the treated and untreated half-piling using procedures outlined in the second or third options. By comparing the results from each half-piling using the same model the actual treatment effect can be directly related to any resulting changes in piling strength.

The advantage of option IV is that it allows direct comparison of strength reduction due to treatment. A disadvantage is that it would require close cooperation between the Navy and the treater. The implication is that subsequent NDT might always require an untreated control.

Apparent Best Choice

Of those four options outlined above the Forest Products Laboratory would opt for the research approach outlined in option I. This option, as previously indicated, allows for a systematic approach to evaluating the several variables that affect the treatment-related strength losses in treated material. The option also allows for the systematic evaluation of the NDT techniques showing the most potential in terms of what technique parameter, when included in a multiparameter model, best predicts strength loss due to treatment. While some additional time may be invested, the amount of full-size testing and time potentially saved in efforts to tests full-size piling should compensate.

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APPENDIX A--LITERATURE SEARCH AND LETTER SURVEY PROCEDURES

The study is divided into two major areas; one covers wood references and the other covers materials references. These major areas are further divided into sections: (1) A review of the wood and general materials literature contained in several large bibliographic data bases; (2) contact with both national and international wood research organizations; (3) contact with industrial and university research organizations involved in NDT research with various types of materials such as wood, polymers, metals and composites; (4) contact with manufacturers of commercial NDT instrumentation having application in wood and other materials; and (5) contact with scientists familiar with or currently working in the area of NDT research in wood. All contacts were critically assessed for technical feasibility for predicting effects of degradation.

Literature Search

A review of wood and general materials literature has been made using computer bibliographic searches run on the following bibliographic data bases:

COMPENDEX
INSPEC--Physics
INSPEC--Electrical and Computer
CHEMISTRY ABSTRACTS
NASA
COMMONWEALTH AGRICULTURAL BUREAU (CAB) ABSTRACTS
NTIS
DDC
MDTADEX
ISMEC

These bibliographic data bases were accessed through one of several commercial vendors. Access to individual data bases owned by a vendor was, done in real time using an online interactive terminal connected between the FPL and the computer. This real-time interactive procedure has allowed the FPL to play an active role in the literature search which includes making preliminary reviews of the records the search has located and, where desired, do additional screening on the records. This additional screening, has applied such criteria as language, accession number, and document type.

Development of an effecient search strategy is the key to making effective use of computer bibliographic searching. Search strategy involves putting together a set of search terms, in hierarchical order, that concisely describes what the user is specifically looking for.

References obtained in the computer bibliographic searches were initially screened on the basis of key words and by reviewing reference abstracts, when available. After the initial screening, each reference selected was carefully reviewed and abstracted. Three criteria were established; abstracted references meeting one or more of the criteria are included in this report. The criteria include:

1. Instrumentation described whould be feasible for nondestructively predicting strength loss.

2. Method or principle described should be useable for nondestructively predicting static or impact bending strength properties.

3. Method or principle described should be capable of predicting energy absorption of material under load. Reviews of abstracted references will be categorized, in the Results section, according to NDT methods used.

The format followed in reviewing each reference for inclusion under one of the several methods categories is:

Describe experimental concepts (i.e., instrumentation, method, or principle) discussed by the author.

What properties was the author measuring, using experimental concepts just described, for property prediction or modeling?

What success was evident in making the property predictions, i.e., coefficient of variation, correlation coefficient, graphic results, etc.?

Additional remarks and recommendations will be made as to whether the methods reviewed under each category are applicable to wood or wood-base material. Methods judged to be applicable will be commented on as to what additional research, if any, is required prior to use on fullsize treated wood piling.

Letter Survey

Contacts in the letter survey were made with the following groups: (1) National and international wood research organization; (2) industrial

and university research organizations involved in NDT research with various types of materials such as wood, polymers, metals, and composites; (3) manufacturers of commercial NDT instrumentation applying to wood and other materials; and (4) scientists familiar with or currently working in the area of NDT research in wood. A total of 38 individuals and organizations responded to letter inquiries. (Listed in Appendix C.) This represents approximately an 80 percent rate of response.

A procedure similar to that described for screening references in the literature part of the review was established for screening responses from individuals and organizations. Those responses selected under one of the three previously mentioned criteria for final screening of the abstracted references are reviewed in the Results section of this report.

APPENDIX B--INSTRUMENTATION AND GRAPHIC NDT RESULTS

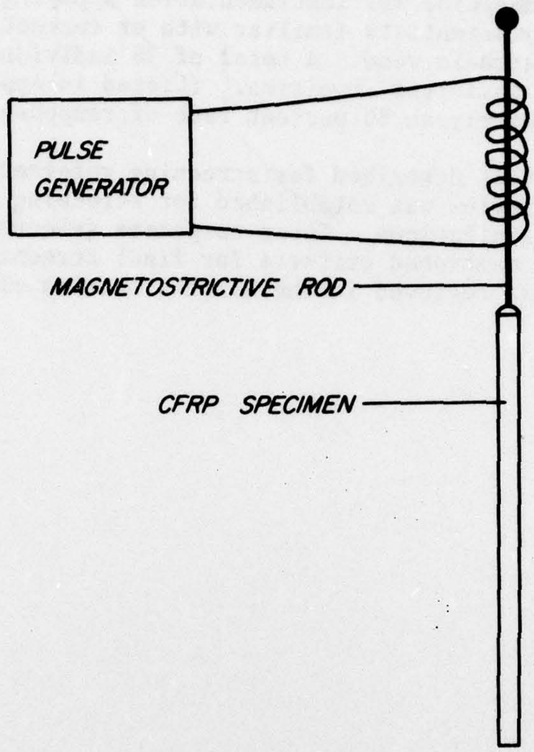

Figure B1.--Diagram of acoustic method used by Brown, Hancox, and Reynolds (10) to produce torsional or longitudinal vibrations in a CFRP test specimens.

(M 146 338)

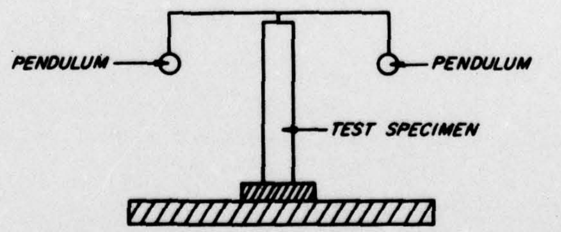

Figure B2.--Diagram of coupled oscillation device shown by Popescu (61).

(M 146 341)

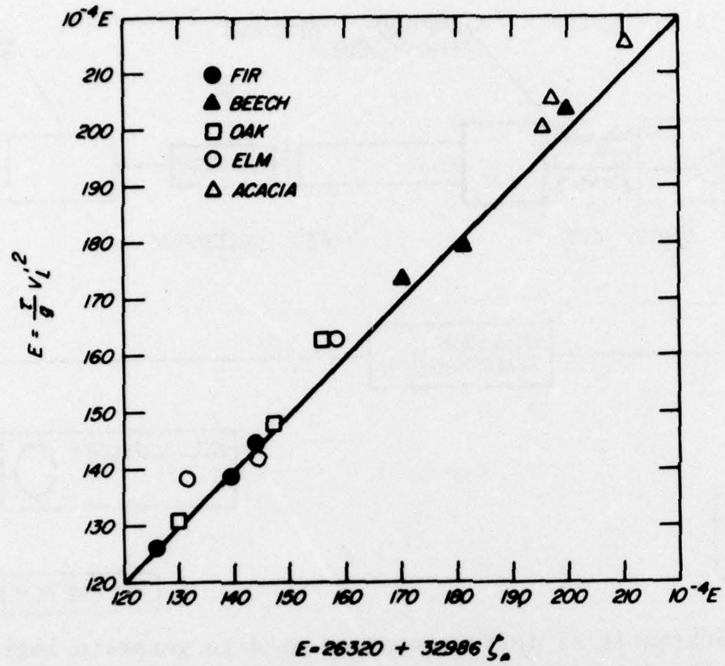

Figure B3.--Plot of coupled oscillation derived E prediction of ultrasonic modulus of elasticity (Popescu (61)).

(M 146 344)

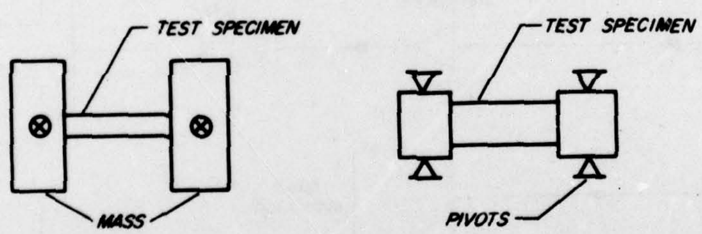

Figure B4.--Balanced resonator (left) top view showing test specimen connecting the two end masses and (right) side view showing pivot points of end masses (Papadakis (55)).

(M 146 337)

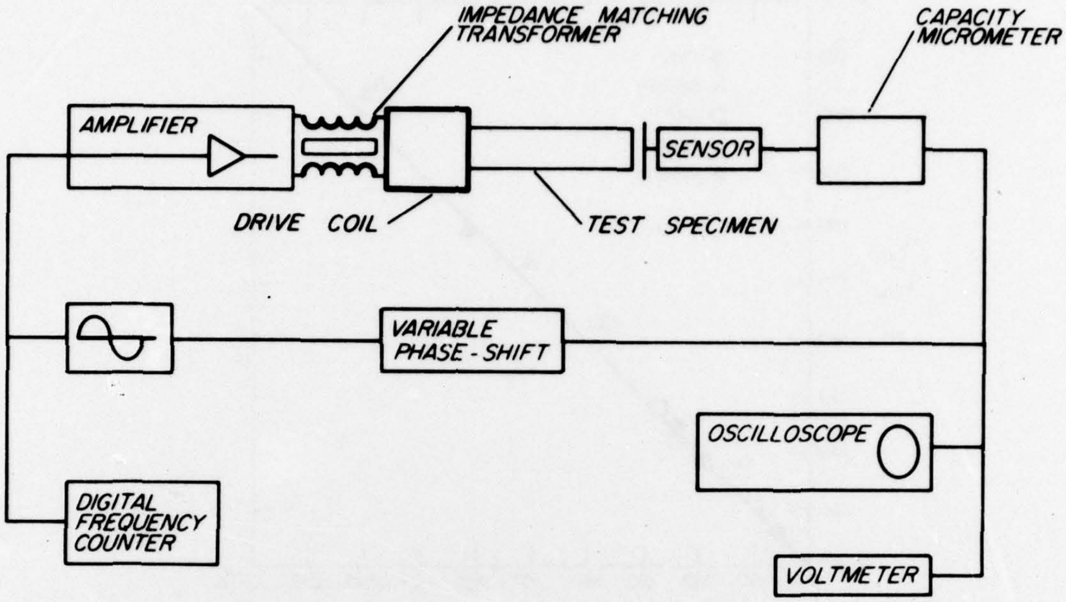

Figure B5.--Schematic of instrumentation used to generate logitudinal vibrations in iron castings as shown by Kovacs and Cole (40).

(M 146 347)

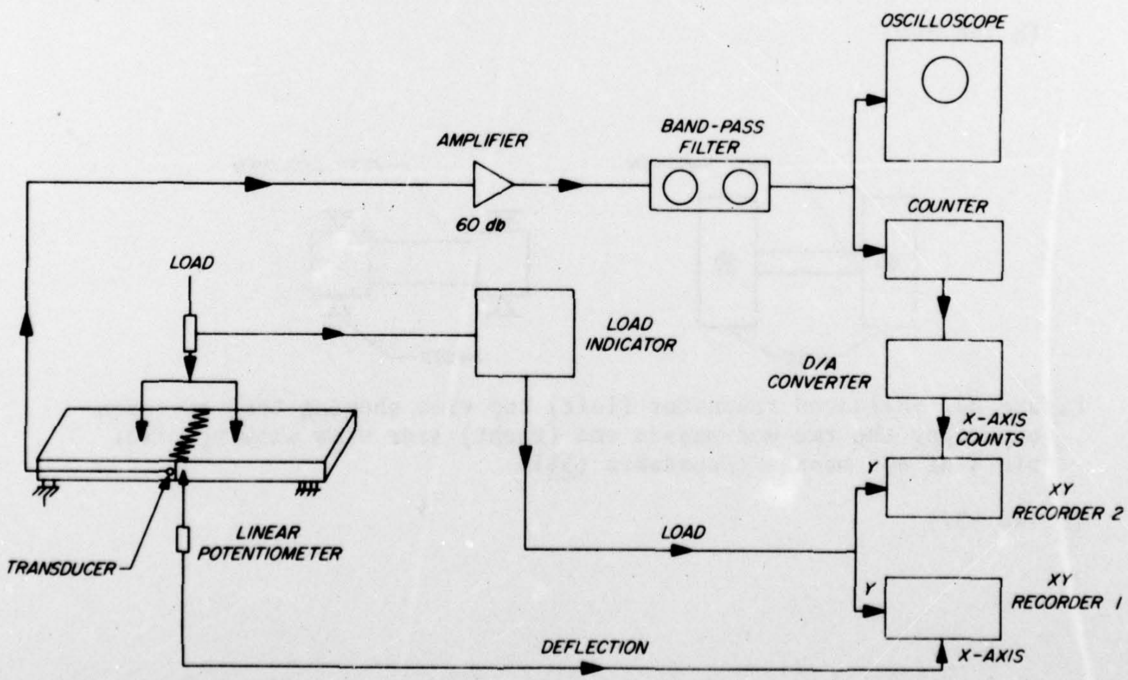

Figure B6.--Schematic representation showing the acoustic emission set up used by Porter et al. (64).

(M 146 482)

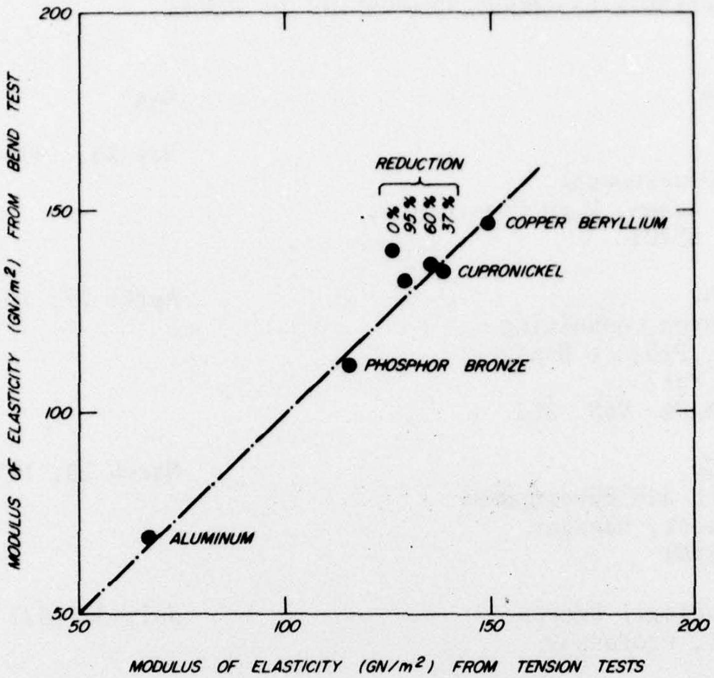

Figure B7.--Graphical comparison of elastic moduli obtained by bend tester and tension tests; Weissmann (82).

(M 146 346)

APPENDIX C--GROUPS RESPONDING TO SURVEY

	From	Date
1.	3M Company Research and Development Mr. Robert M. Adams, Vice President St. Paul, MN 55101	May 23, 1977
2.	B. C. Research Marine Structures Consulting Mr. J. J. Agi, Project Manager 3650 Wesbrook Mall Vancouver, CANADA V6S 2L2	April 27, 1977
3.	Weyerhaeuser Co. Lumber Research and Development Mr. Wayne Bennett, Manager Tacoma, WA 98401	March 25, 1977
4.	Instytut Technologii Drewna Dr. R. Bobicki, Professor 60-654 Pognan ul. Winiarski I POLAND	July 5, 1977
5.	Commonwealth Scientific and Industrial Research Mr. P.A.V. Bryant Timber Research Unit P.O. Box 395 Pretoria SOUTH AFRICA	July 28, 1977
6.	Swedish Forest Products Research Laboratory Mr. S. Casselbrandt P. O. Box 5604 Drotten, Kristinus 67 S-11486 Stockholm, SWEDEN	July 13, 1977
7.	Sandia Laboratories Materials and Processes Mr. R. S. Classen, Director Albuquerque, NM 87115	September 14, 1977

From	Date
8. Metals and Ceramics Division Air Force Materials Laboratory Nondestructive Evaluation Branch Mr. Robert L. Crane Wright-Patterson Air Force Base OH 45433	May 25, 1977
9. Princes Risborough Laboratory Building Research Establishment Mr. W. T. Curry Aylesbury Buckinghamshire HP17 9PX ENGLAND	March 23, 1977
10. Engineering Physics Laboratory E. I. Du Pont de Nemours and Company Mr. L. G. Glasser, Director Wilmington, DE 19898	April 27, 1977
11. Eastern Forest Products Laboratory Canadian Forestry Service Mr. A. P. Jessome, Research Scientist 800 Montreal Road Ottawa, CANADA KIA OW5	April 26, 1977
12. James Electronics Inc. Mr. John A. Kennedy 4050 North Rockwell Street Chicago, IL 60618	May 23, 1977
13. General Electric Company Research and Development Center Quality Technology Branch Dr. Thomas G. Kincaid, Manager Non-Destructive Testing Program Building 37, Room 5032 P. O. Box 43 Schenectady, NY 12301	July 26, 1977
14. Commonwealth Scientific and Industrial Research Organization Division of Building Research Dr. R. H. Leicester Officer-in-Charge, Structures Section Graham Road Highett, Victoria 3190 AUSTRALIA	March 28, 1977

	From	Date
15.	General Electric Company Research and Development Center Chemical and Structural Analysis Branch Materials Characterization Laboratory Mr. E. Lifshin, Manager P. O. Box 43 Schenectady, NY 12301	June 24, 1977
16.	Southwest Research Institute Department of Materials Science Mr. U. S. Lindholm, Director 8500 Culebra Road P. O. Drawer 28510 San Antonio, TX 78284	May 6, 1977
17.	Western Forest Products Laboratory Canadian Forestry Service Timber Engineering Mr. T. W. Littleford, Section Head 6620 NW. Marine Drive Vancouver, British Columbia CANADA V6T 1X2	March 29, 1977
18.	E. I. Du Pont de Nemours and Company Engineering Technology Laboratory Engineering R&D Division Mr. E. M. Mahla, Director Wilmington, DE 19898	May 6, 1977
19	Canada Centre for Mineral and Energy Technology Construction Materials Section Mr. V.M.L. Malhotra, P. E. Head 555 Booth Street Ottawa, CANADA K1A OG1	June 6, 1977
20.	Battelle Columbus Laboratories Fabrication and Quality Assurance Section Mr. R. P. Meister, Associate Manager 505 King Avenue Columbus, OH 43201	May 10, 1977

	From	Date
21.	National Bureau of Standards United States Department of Commerce Nondestructive Evaluation Program Mr. Leonard Mordfin, Deputy Manager Washington, D. C. 20234	March 30, 1977
22.	Forest Products Laboratory Norwegian Technological Institute Mr. Karl Morkved Box 337, Blindern Oslo 3, NORWAY	March 30, 1977
23.	Inspection Instruments (NDT) Ltd. Mr. P. R. Phillips 32 Duncan Terrace London, ENGLAND N1 8BS	April 19, 1977
24.	Porter Engineering Limited Dr. A. W. Porter 5800 Cedarbridge Way Richmond, BC CANADA V6X 247	June 22, 1977
25.	Oregon State University Department of Forest Products Dr. Helmuth Resch, Head Corvallis, OR 97331	March 29, 1977
26.	Erdeszeti Es Faipari Egyetem Dr. F. Ronai Bojcsy-Zsilinsky U.4 9400 Sopron HUNGRY	July 20, 1977
27.	University of California, Berkeley College of Natural Resources Forest Products Laboratory Dr. Arno P. Schniewind, Professor Richmond, CA 94804	April 20, 1977
28.	Institut fur Holzforschung Holztechnik Der Universitat Munchen Dr. H. Schulz, Professor 8 Munchen 13 Winzererstrasse 45, WEST GERMANY	March 29, 1977

	From	Date
29.	C.N.S. Electronics Ltd. Mr. G. M. B. Selous 61-63 Holmes Road London, ENGLAND NW 5 3AN	April 20, 1977
30.	Balteau Electric Corp. Mr. Joseph L. Silva Technical Specialist 63 Jefferson Street Stamford, CT 06902	May 4, 1977
31.	Aluminum Company of America Alcoa Technical Center Mr. H. A. Traenkner Materials Manager Alcoa Center, PA 15069	May 2, 1977
32.	Houtinstituut TNO Dr. A. van der Velden Schoemakerstraat 97 (Zuidpolder) Postbus 151 Delft, HOLLAND	August 11, 1977
33.	The Firestone Tire & Rubber Company Central Research Laboratories Mr. J. D. Walter, Assistant Director Akron, OH 44317	June 22, 1977
34.	Sandia Laboratories Acceptance Technology Division Mr. Alec R. Willis, Supervisor Livermore, CA 94550	May 23, 1977
35.	Northeast Electronics Corporation Mr. R. V. Workholz, V. P. Engineering Airport Road Concord, NH 03301	April 18, 1977
36.	Army Materials and Mechanics Research Center Mr. E. S. Wright, Director Watertown, MA 02172	July 15, 1977

37. Kyoto University April 15, 1977
Wood Research Institute
Professor T. Yamada
Uji, Kyoto
JAPAN

38. Union Carbide Corp. April 28, 1977
Carbon Products Division
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